

# **Dust Emission Optimization with Satellite Remote Sensing: Application to CLAEERO**

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**AAROMA Group**

**(Aerosol, Radiation, Remote-sensing & Observation-based  
Modeling of Atmosphere)**

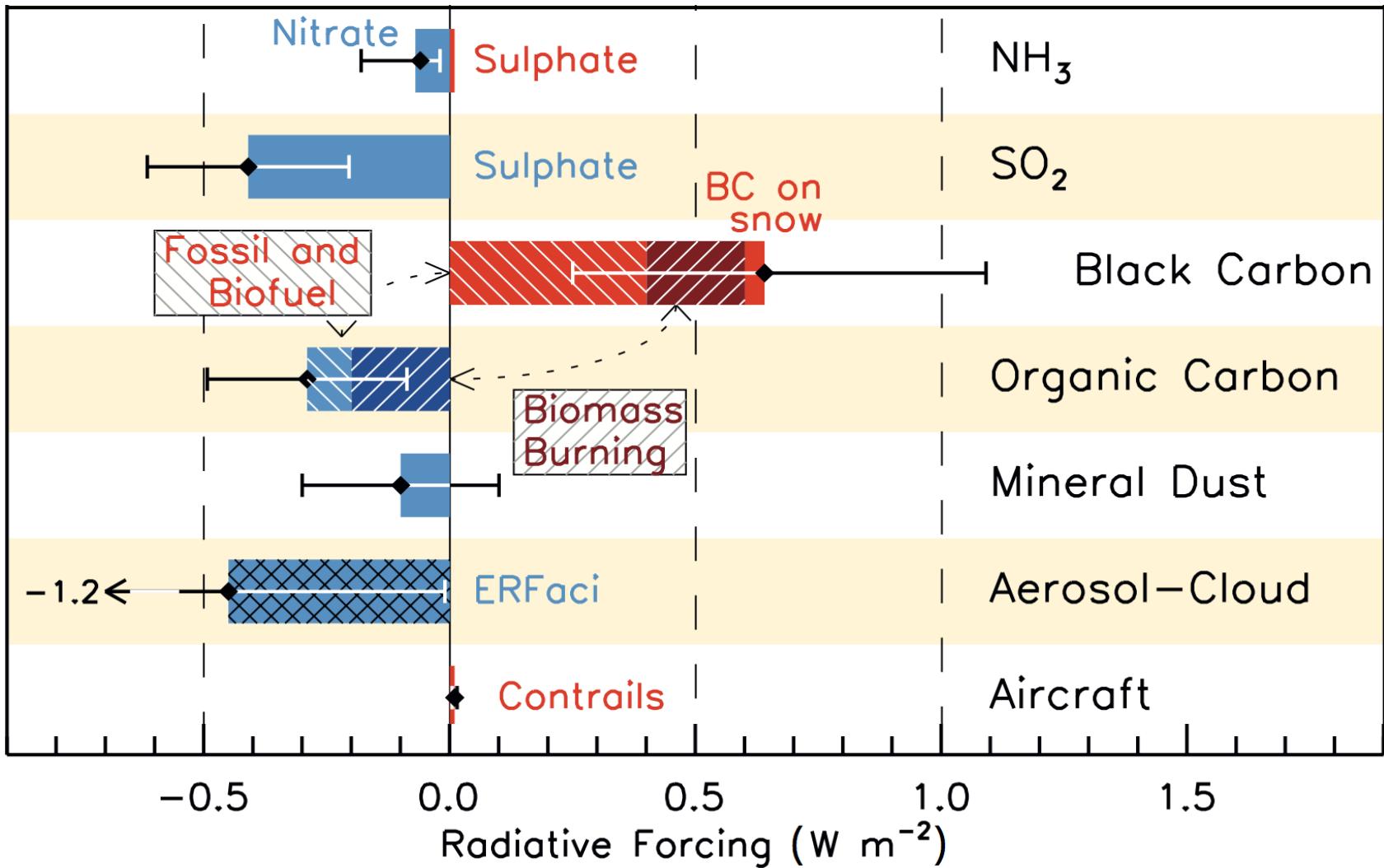
**Univ. of Nebraska – Lincoln**

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**Daven Henze, Li Zhang**

**Univ. of Colorado**

# Forcing of each aerosol component (AR5)



The sign of the dust forcing is still unknown.

# Motivation

**Motivated by Wielicki et al. (2013, BAMS):**

- CLARREO enables two new approaches to climate analysis:
  - benchmark spectral fingerprinting
  - reference inter-calibration
- CLARREO measures with high spectral resolution over 95% of the spectrum of Earth's thermal emitted radiation ( $200\text{--}2000\text{ cm}^{-1}$  or  $5\text{--}50\text{-}\mu\text{m}$  wavelength) and solar reflected radiation ( $350\text{--}2300\text{ nm}$ ) for the first time.
- Spectral fingerprint linearity has been shown for both IR and SW.

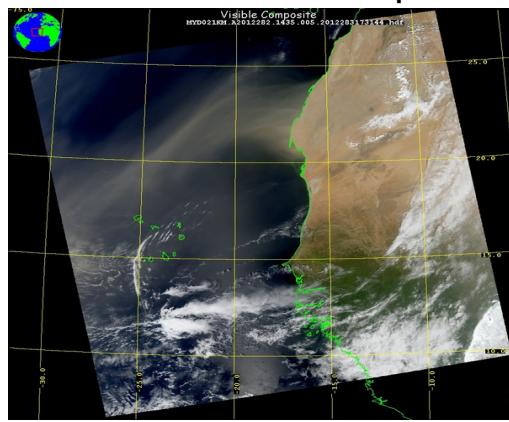
**We like to ask the question:**

- To what extent does the long-term variability of dust emissions manifest first-order changes in large-scale general circulation that can be possibly recovered from the satellite-based spectral climate?
- Across what temporal and spatial scales are these features evident in spectral climate data?

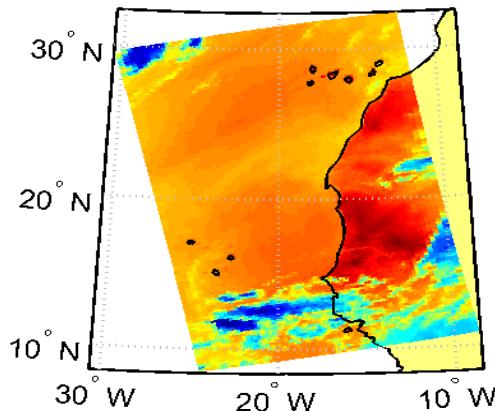
# Dust spectral signature

In shortwave, spectrally flat; In infrared, negative slope in BT in  $820\text{-}920\text{ cm}^{-1}$  ( $12.2\text{-}10.87\text{ }\mu\text{m}$ ).  
We think dust can be best characterized by using SW (UV+blue in particular) + IR. CALERRO is well suited for this.

MODIS Visible Composite

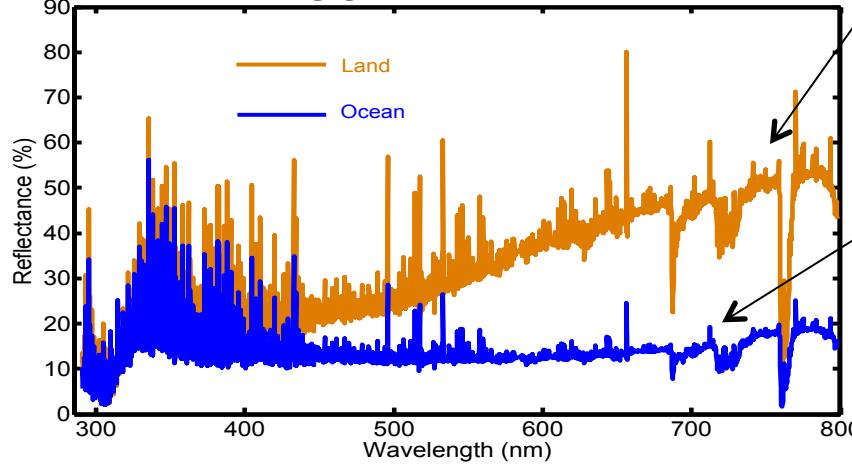


AIRS Level 1B 11  $\mu\text{m}$  BT



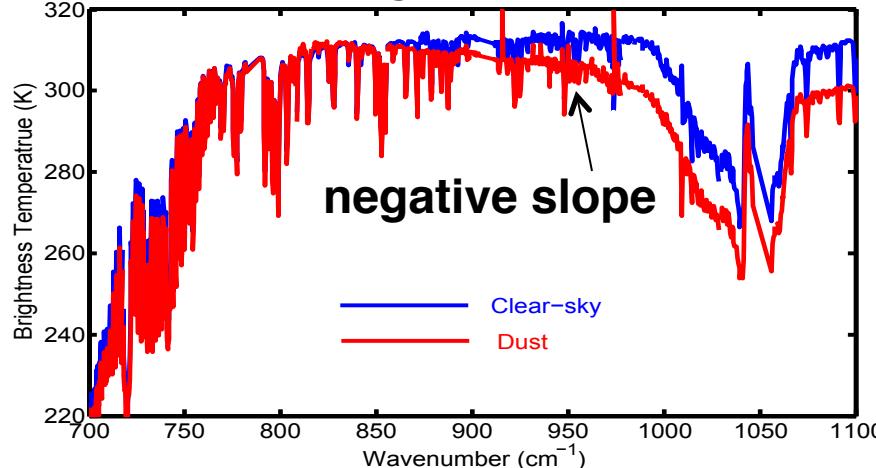
dominated by surface ref.

GOME2

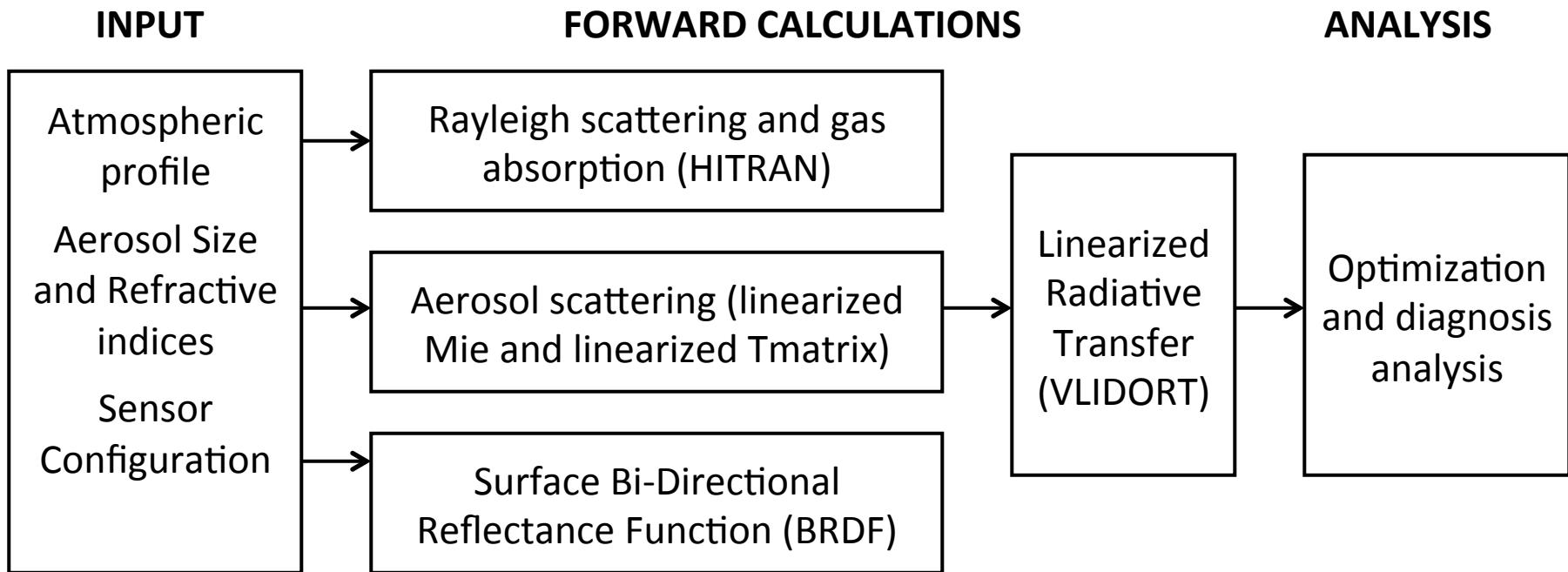


Dominated by dust

AIRS



# UNified & Linearized Vector Radiative Transfer Model (UNL-VRTM)

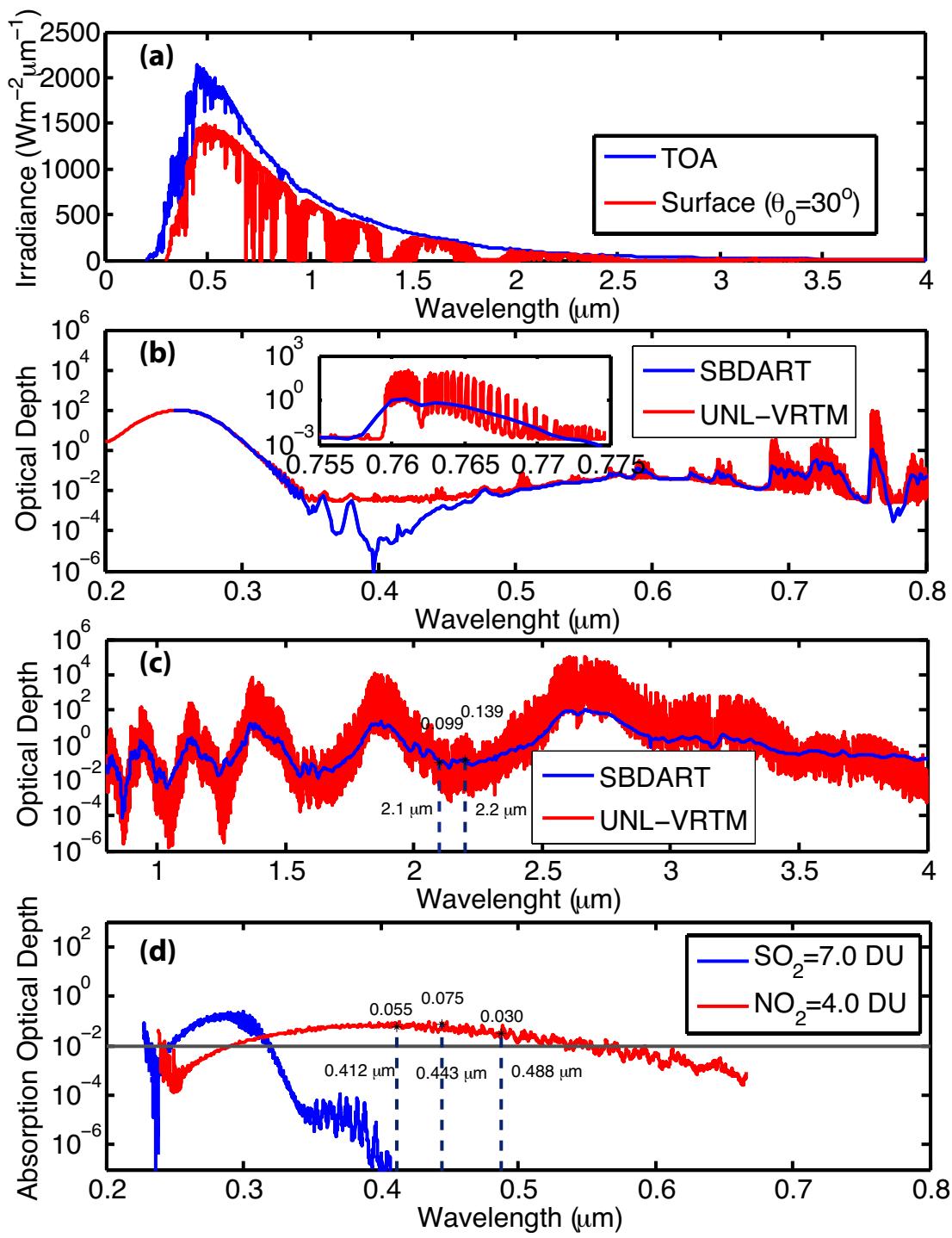


Spurr, R., J. Wang, et al., Linearized T-matrix and Mie scattering computations, *J. Quant. Spectrosc. Radiat. Transfer.*, 113, 425-439, 2012.

Wang, J. , X. Xu, et al., A numerical testbed for remote sensing of aerosols, and its demonstration for evaluating retrieval synergy from a geostationary satellite constellation of GEO-CAPE and GOES-R, *J. Quant. Spectrosc. Radiat. Transfer.*, 146, 510-528, 2014.

# Unique feature of UNL-VRTM – Gas Absorption

Note:  $\text{SO}_2$  and  $\text{NO}_2$  emissions have changed in the past 3-4 decades because of (a) Clean-air policies in Europe and US, and (b) fast-growing economy in Asia and other developing regions.

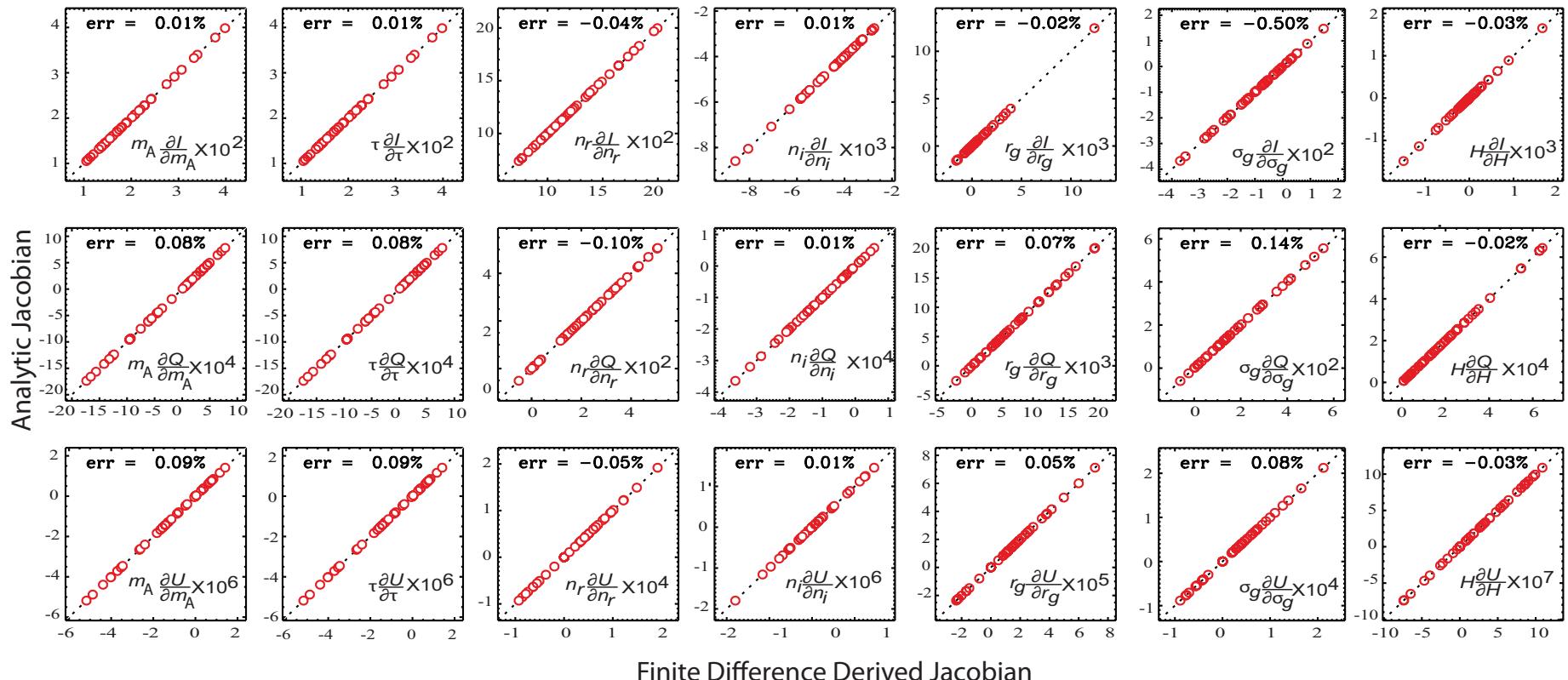


# Unique feature of UNL-VRTM – fully linearized for Jacobian calculations

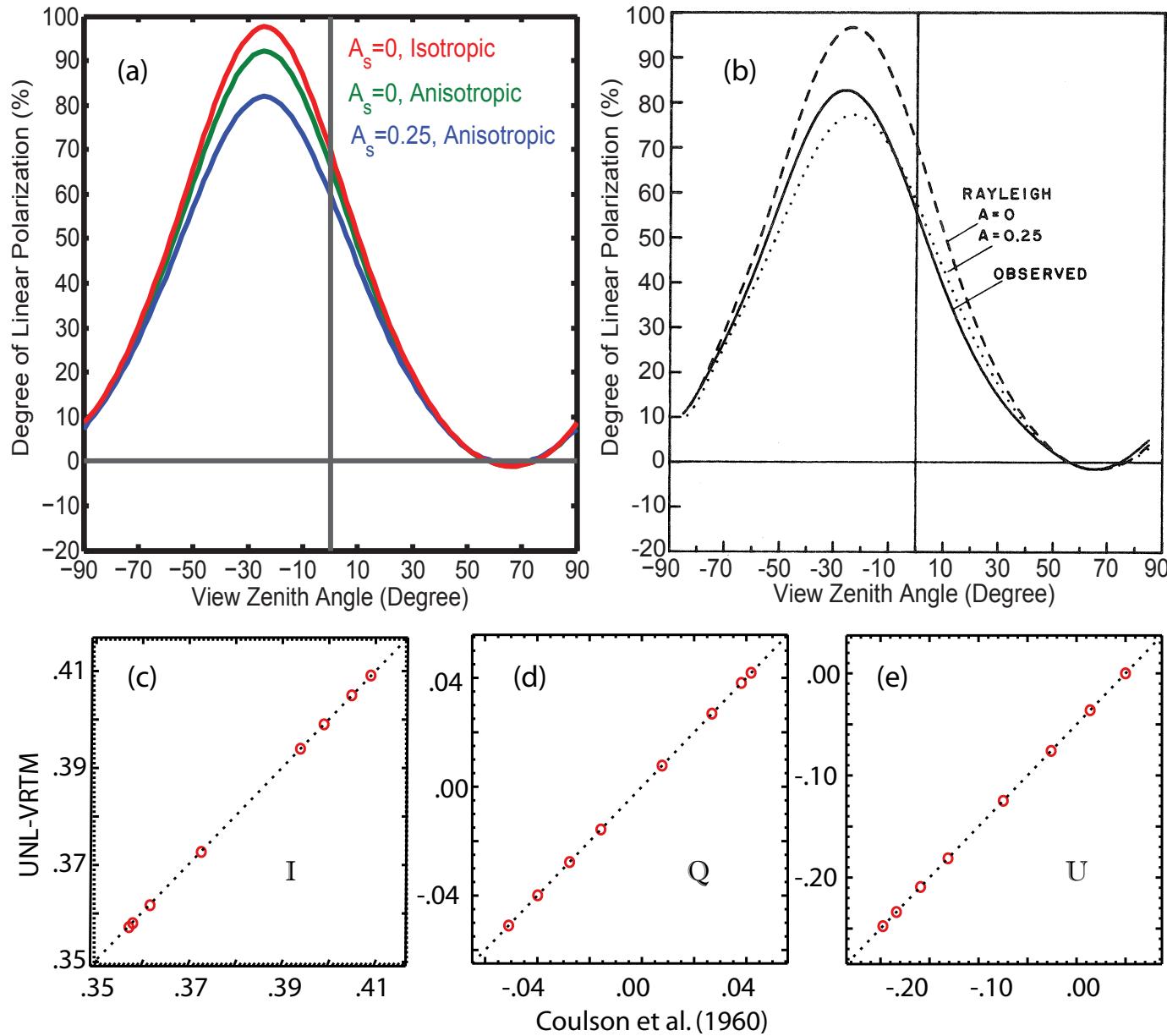
Calculation of Jacobians of any Stokes parameter  $\xi$  with respect to any aerosol parameter  $x$  (such as size parameter) proceeds according to

$$x \frac{\partial \xi}{\partial x} = x \begin{bmatrix} \frac{\partial \xi}{\partial \tau_L} & \frac{\partial \xi}{\partial \omega_L} & \langle \frac{\partial \xi}{\partial \mathbf{B}_L^j} \rangle_{j=0,J} \end{bmatrix} \begin{bmatrix} \frac{\partial \tau_L}{\partial x} & \frac{\partial \omega_L}{\partial x} & \langle \frac{\partial \mathbf{B}_L^j}{\partial x} \rangle_{j=0,J} \end{bmatrix}^T$$

**Linearized VRTM code**    **Linearized Mie code**

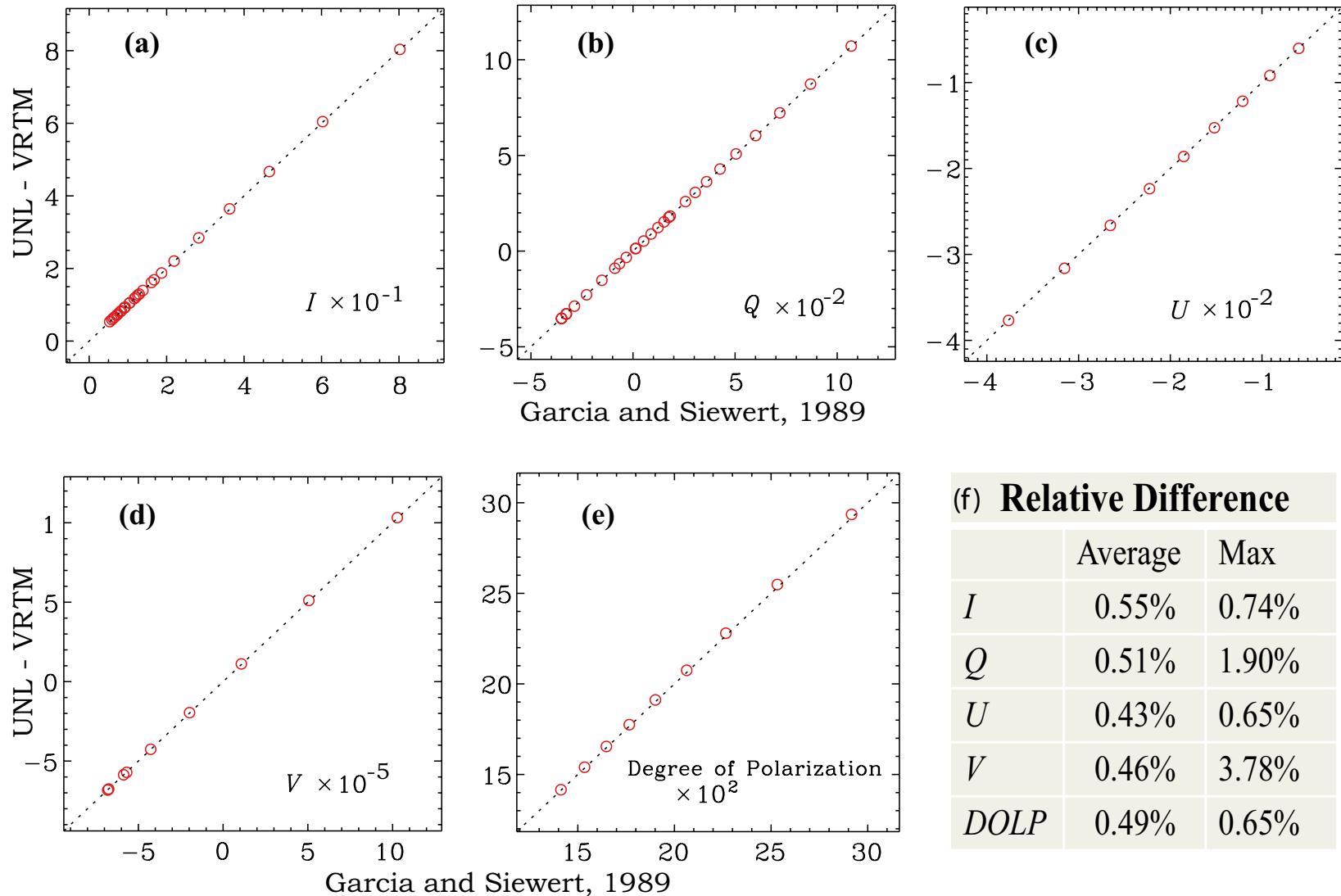


# Validation Pure Rayleigh-Scattering Atmosphere



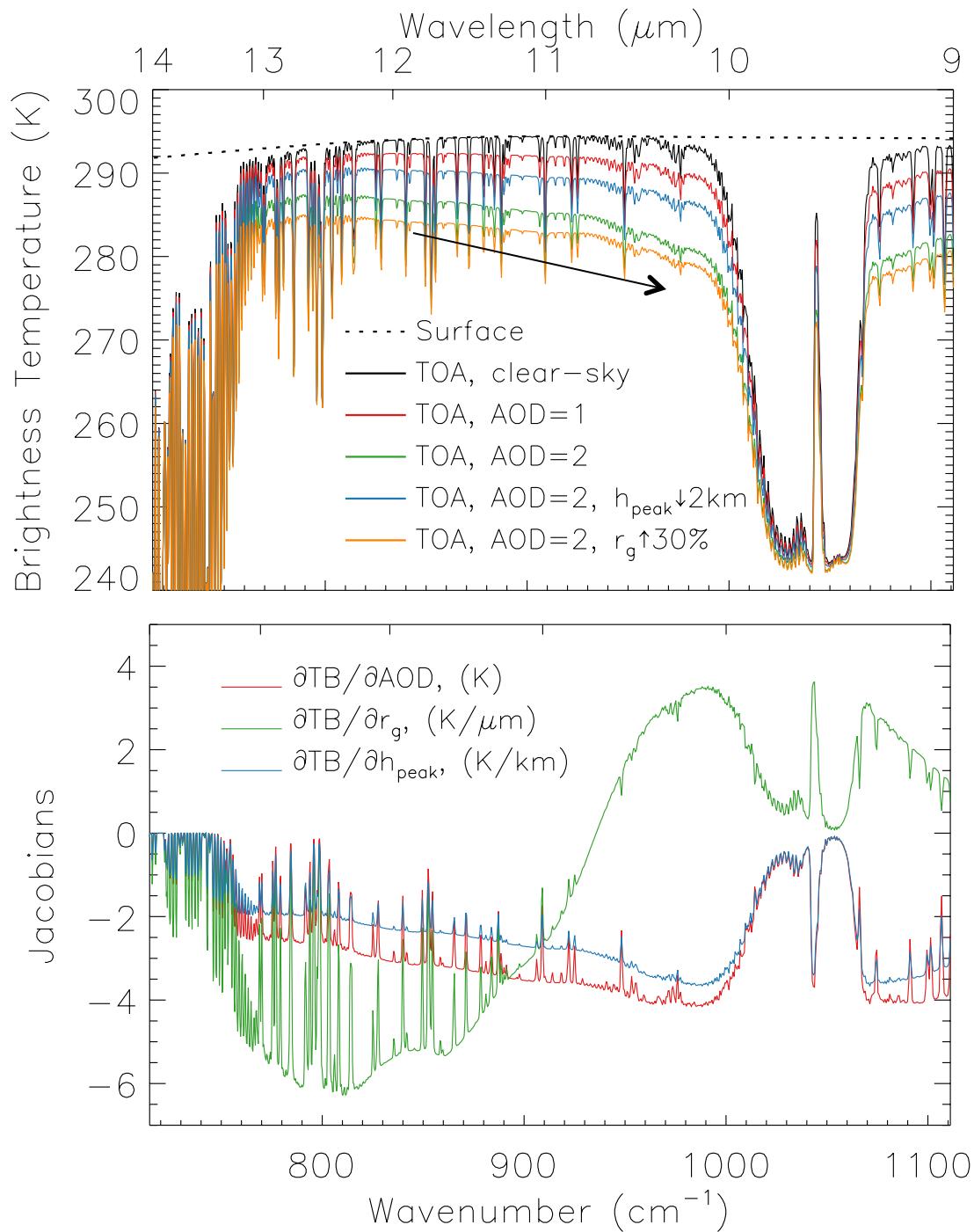
# Validation

## Atmosphere with aerosols

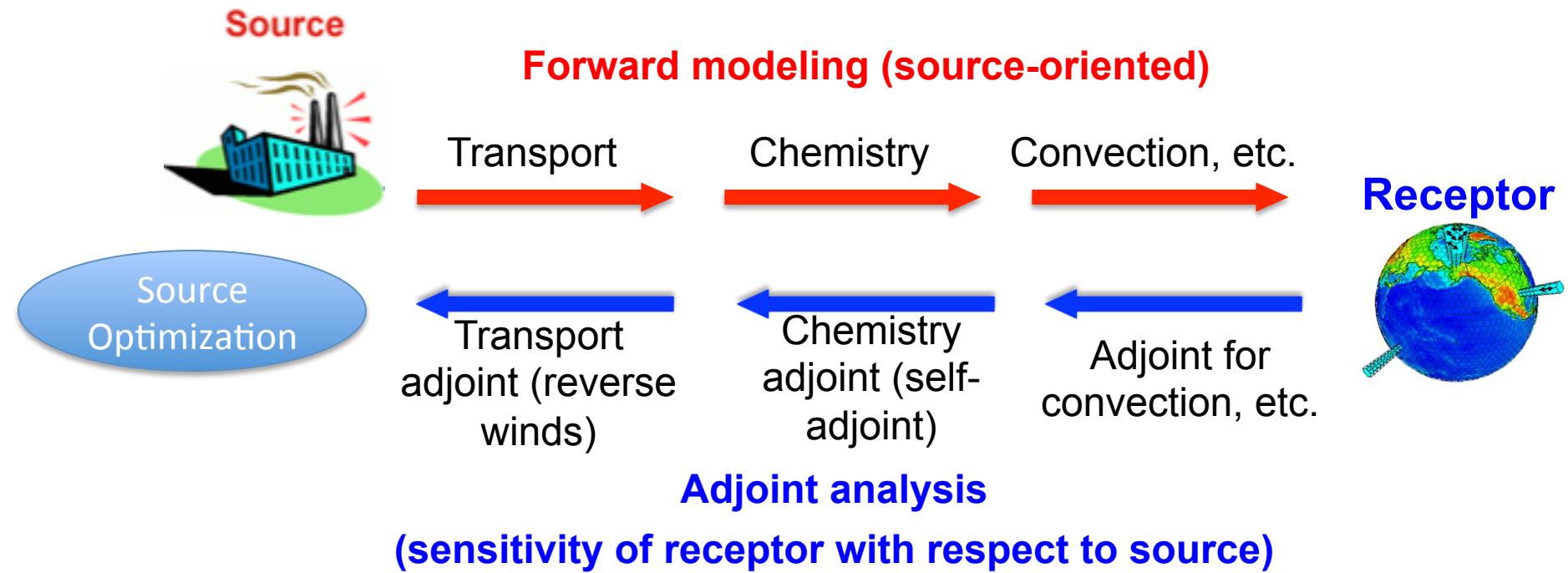


# Hyper-spectral simulation of dust effect in IR including sensitivity of BT to dust particle size and layer height.

**Top:** simulated brightness temperature in 9 – 14  $\mu\text{m}$  for various atmospheric conditions. **Bottom:** corresponding Jacobians with respect to dust height, size, and AOD. Unless labeled otherwise,  $rg = 0.5 \mu\text{m}$ ,  $h_{\text{peak}} = 3.0 \text{ km}$ ,  $\text{AOD} = 2.0$  at 0.55  $\mu\text{m}$



# GEOS-chem adjoint modeling



The adjoint provides receptor→ source relationship.

$$E \frac{\partial C}{\partial E}$$

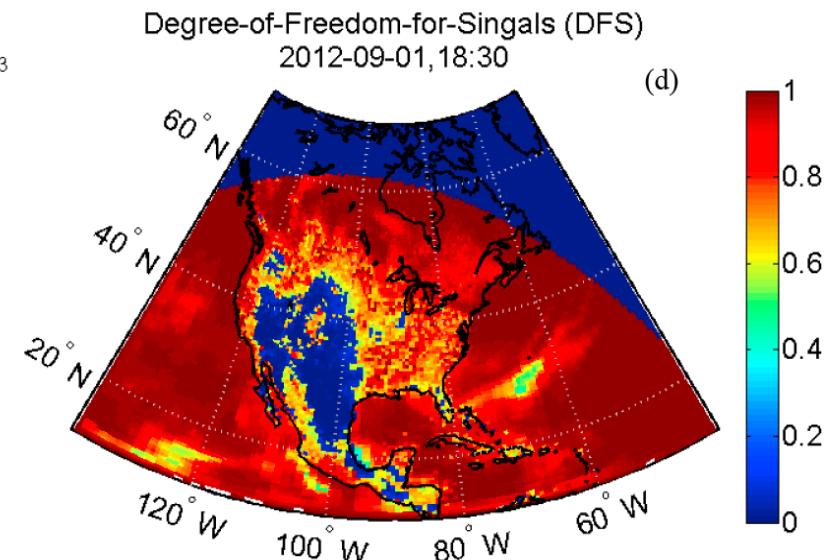
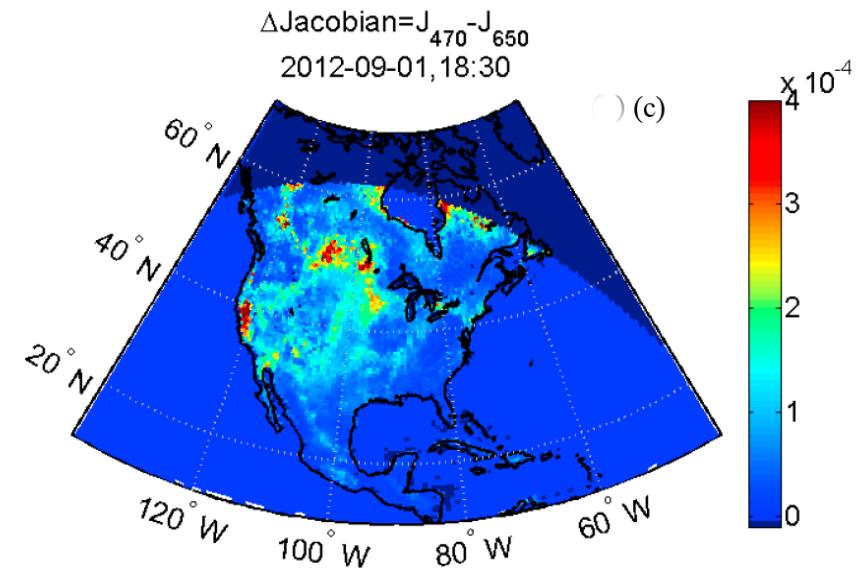
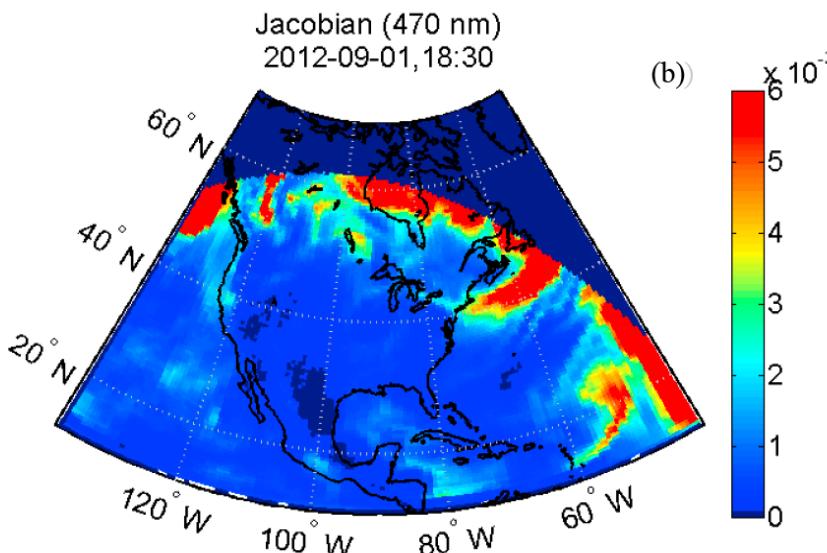
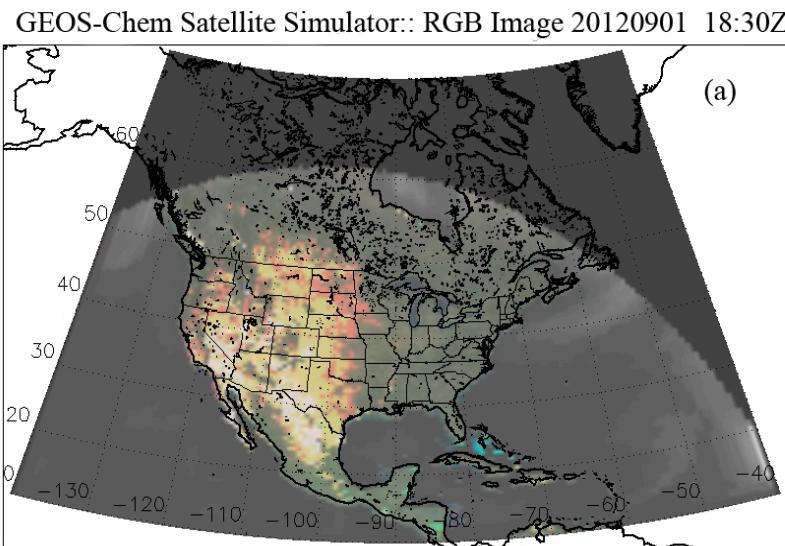
UNL-VRTM provides:

$$C \frac{\partial I}{\partial C}$$

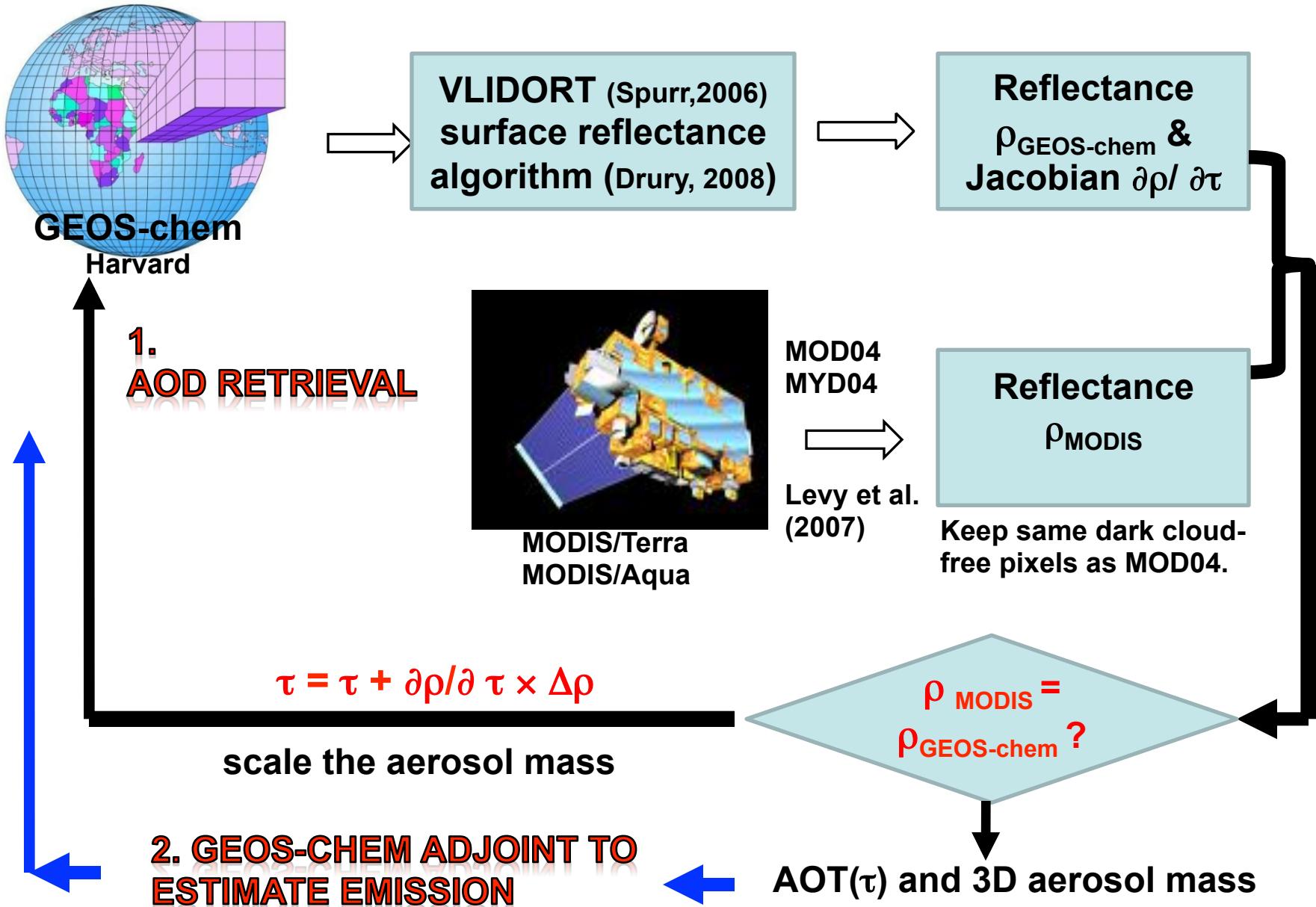
So, **GEOS-Chem adjoint and UNL-VRTM together provide a powerful tool to examine the information content of aerosol parameter and aerosol source function in the satellite measurements.**

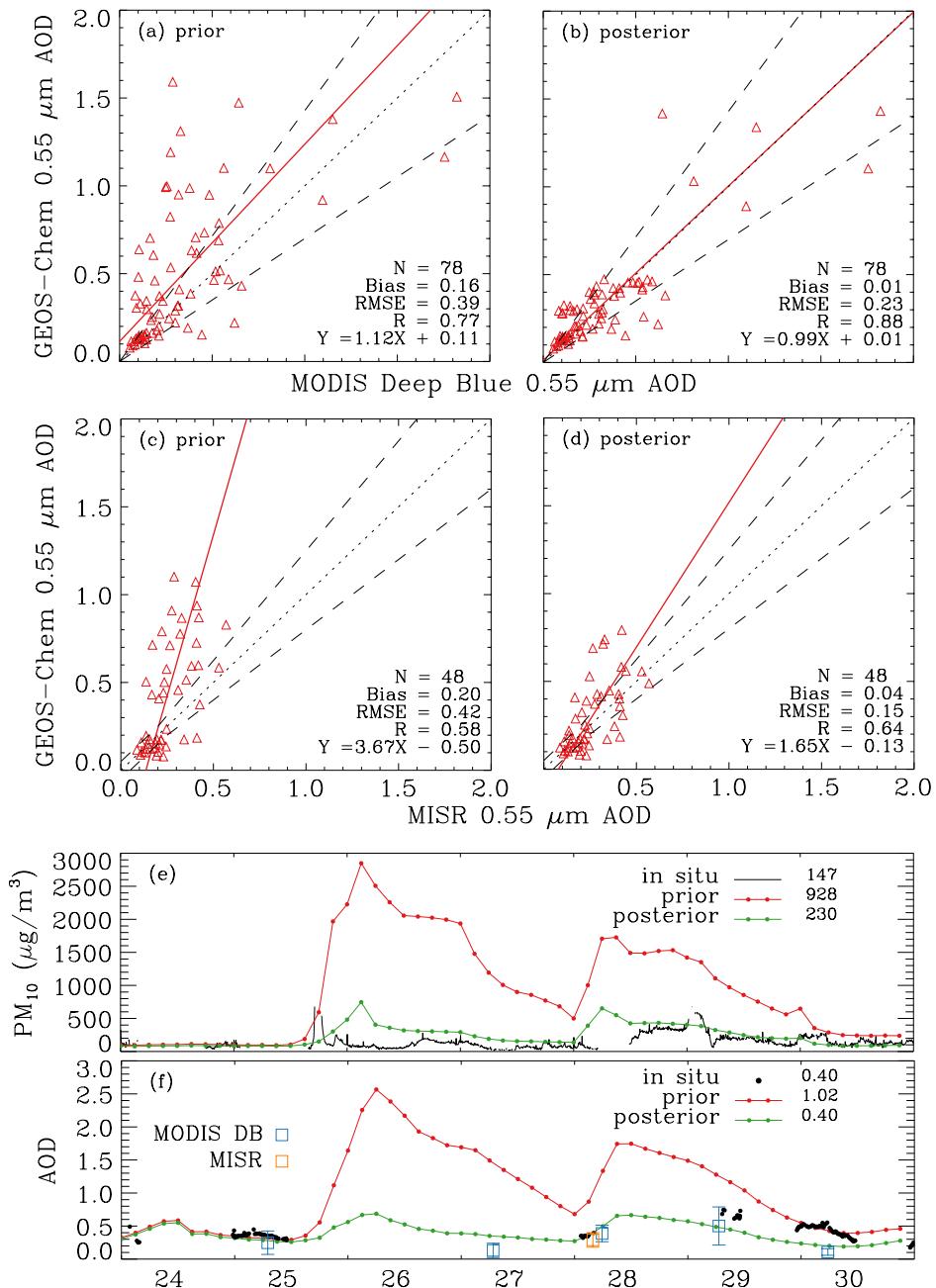
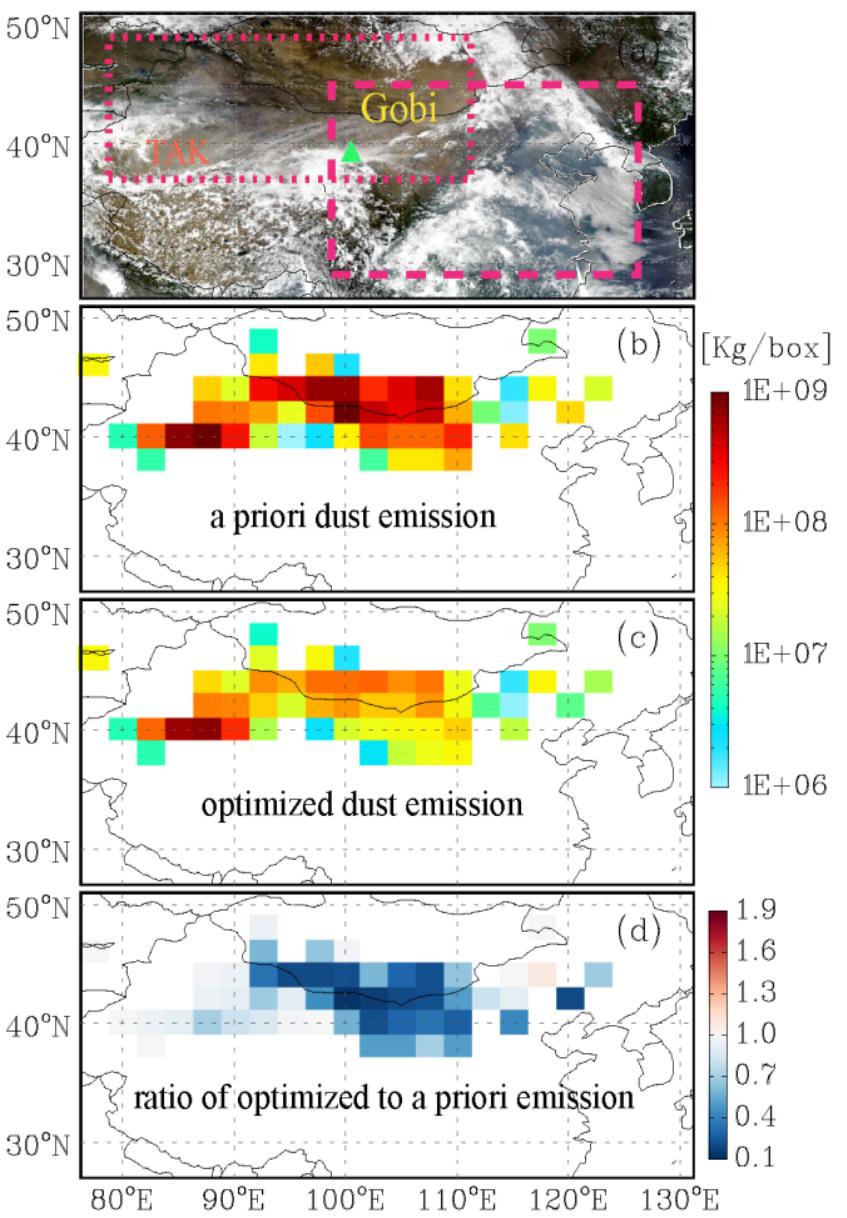
# Forward calculation of synthetic data

(a) A clear-sky RGB image in the TEMPO's viewing geometry, (b) Jacobians of TOA intensity in blue w.r.t. AOD, (c) differences of Jacobians between blue and red, and (d) DFS for AOD retrievals.



# Use reflectance to optimize dust emission 2-step approach





# Can we use reflectance to constrain dust parameterization?

Inputs: Wind speed, friction velocity ( $u_*$ ), soil texture and moisture, Land surface properties



Ideal threshold wind friction v:

$$u_{*t} = f(D_0, \rho_p)$$



Real threshold wind friction v affected by drag partition (turned off) and moisture inhabitation:

$$u_{*t}(\theta, z_{0,m}) = u_{*t} \cdot f(\theta) \cdot f(z_{0,m})$$



Horizontal saltation flux:

$$Q_s(u_{*t}; u_*) = \begin{cases} \frac{C_k \rho_a}{g} u_*^3 \left(1 - \frac{u_{*t}}{u_*}\right) \left(1 + \frac{u_{*t}}{u_*}\right)^2, & \text{if } u_* > u_{*t} \\ 0, & \text{if } u_* \leq u_{*t} \end{cases}$$

Vertical entrainment flux:

$$F_{d,j} = T_0 f_{\text{bare}} S \alpha Q_s \sum_{i=1}^3 M_{i,j}$$

$f_{\text{bare}}$  Fraction of bare soil

$S$  Soil “erodibility” (GOCART)

$\alpha$  Sand blasting efficiency factor (**Fixed**)

$M_{i,j}$  Mass fraction of transport bin  $j$  from parent soil mode  $i$



Zender et al [2003]

Iversen and White [1982]

Marticorena and Bergametti [1995]

Fairlie et al [2007]

# Adjoint Implementations

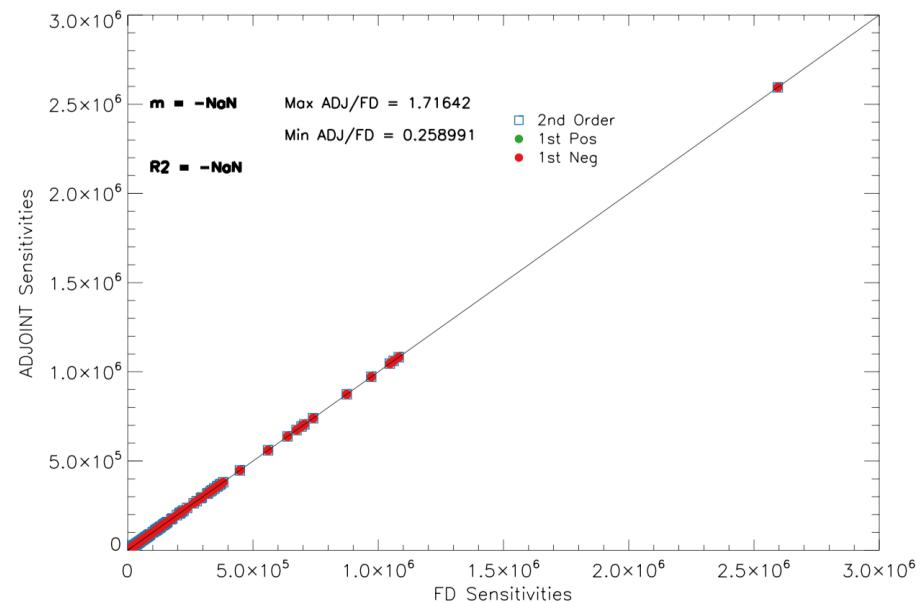
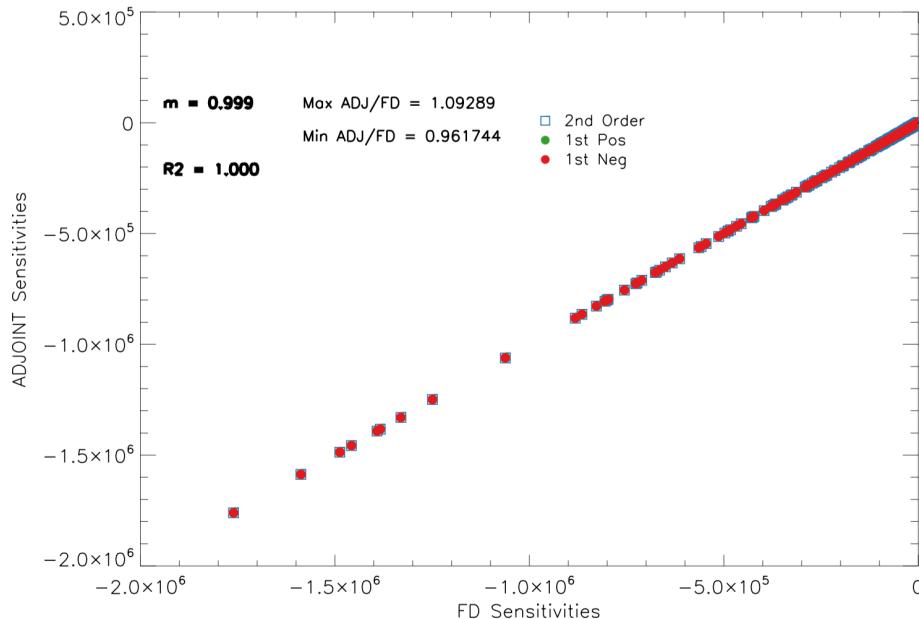
- Gradients of emission flux with respect to  $S'$  and  $u_{*t}$ :

$$\frac{\partial F_d}{\partial S'} = f_{\text{bare}} \int_{u_{*t}}^{u_{*\max}} Q_s(u_{*t}; u_*) p(u_*) du_*$$

$$\frac{\partial F_d}{\partial u_{*t}} = f_{\text{bare}} S' \int_{u_{*t}}^{u_{*\max}} \frac{\partial Q_s(u_{*t}; u_*)}{\partial u_{*t}} p(u_*) du_*$$

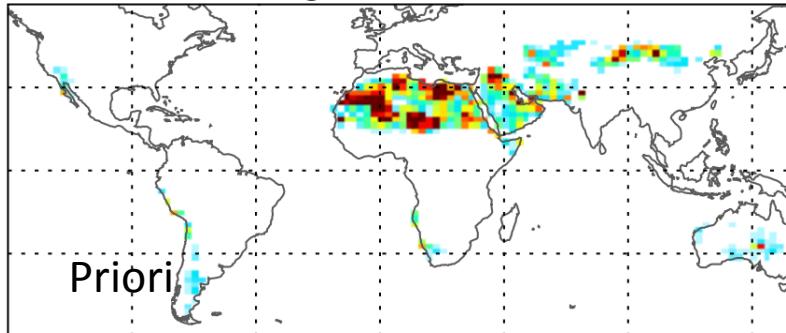
$$\frac{\partial Q_s(u_{*t}; u_*)}{\partial u_{*t}} = \frac{c_K \rho_a}{g} u_*^3 \left[ \frac{1}{u_*} - \frac{2u_{*t}}{u_*^2} - \frac{3u_{*t}^2}{u_*^3} \right].$$

- Adjoint gradient verification:

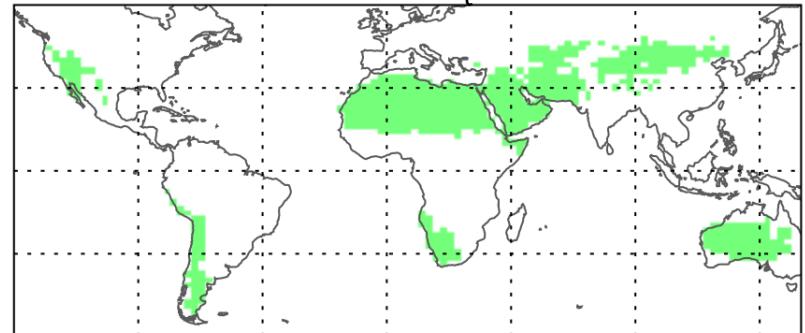


# Optimization Results with MODIS-DB AODs (June 2008)

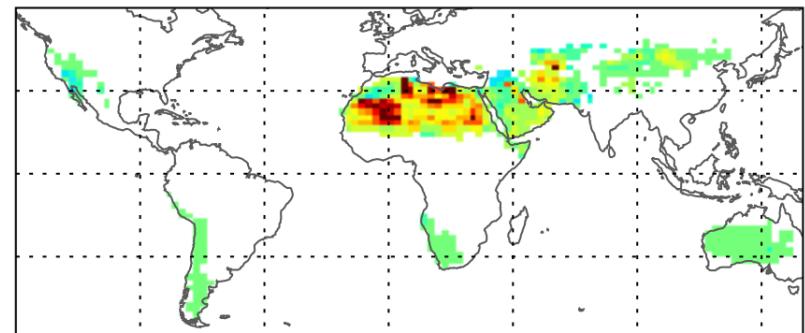
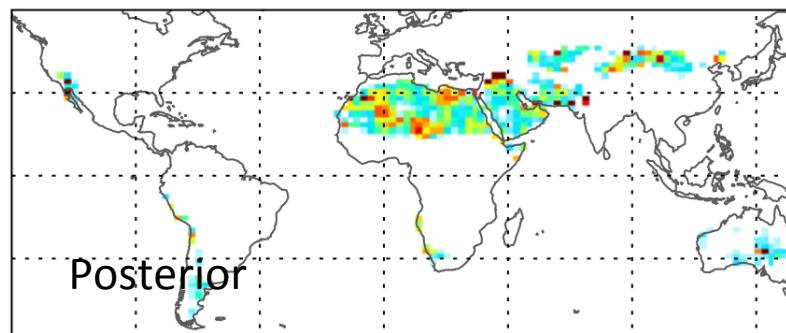
S



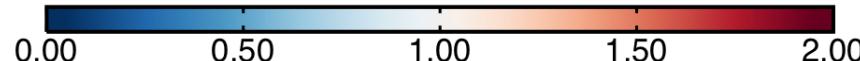
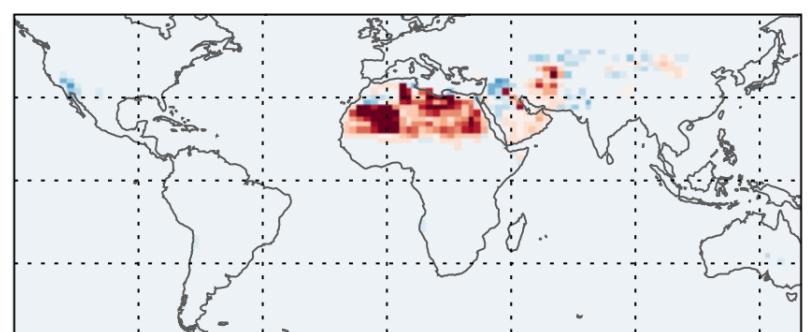
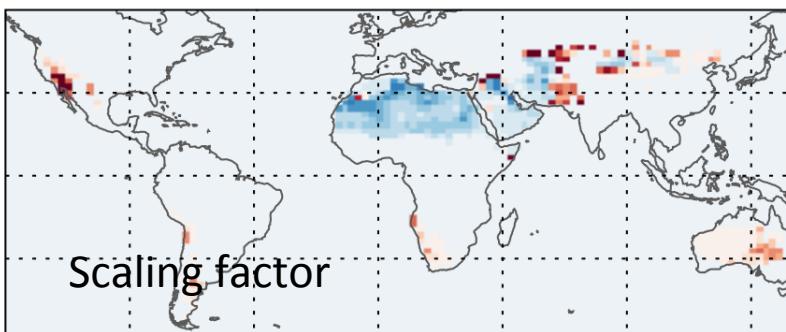
$U_{*t}$



Posterior

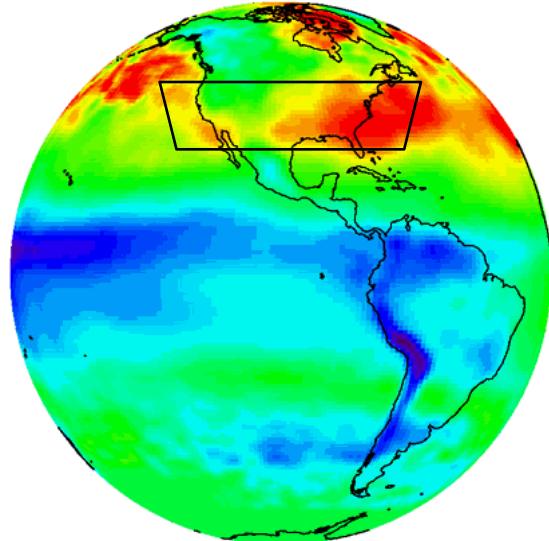


Scaling factor

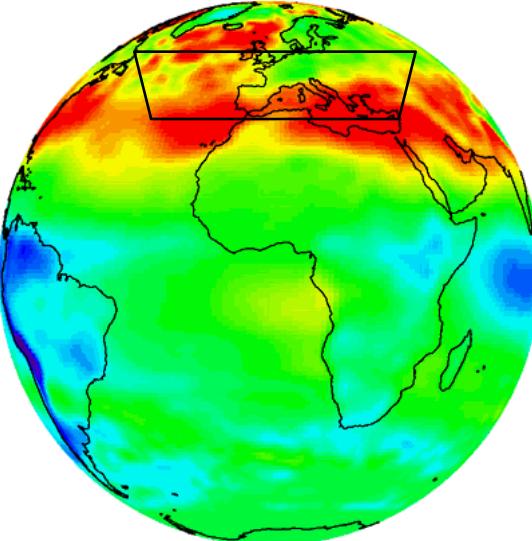


# **CLARREO reference inter-calibration for GEO can further help use of GEO to constrain aerosol emissions**

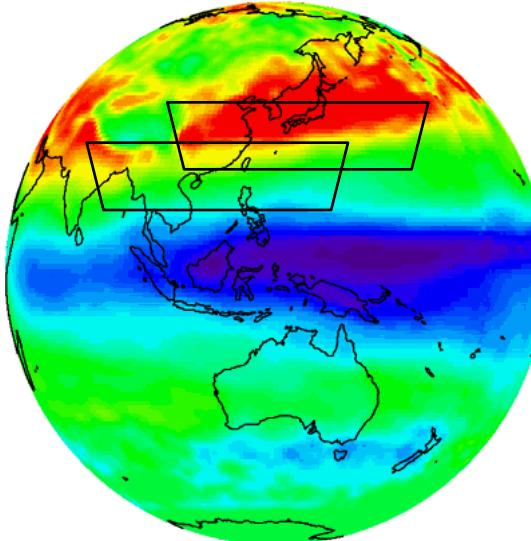
**GEO mission planned for AQ in 2018-2019.**



**NASA GEO-CAPE  
NOAA GOES R/S**



**ESA, Eumetsat  
Sentinel-4 + MTG**



**KARI, ME GEMS  
JAXA GMAP-ASIA**

**Image courtesy: Jay Al-Saadi  
CEOS on Atmospheric Composition Constellation**

**GEO constellation for AQ have been endorsed by various international protocols and conventions (IGACO, GEO, WMO GAW).**

# Funded tropospheric chemistry mission parameters (as of 5/2014)

From Jay Al-Saadi

	Europe Sentinel 4	USA TEMPO	Korea GEMS	Europe Sentinel 5 Precursor TROPOMI
<b>Orbit</b>	Geostationary	Geostationary	Geostationary	Low-Earth
<b>Domain</b>	Europe and surrounding	North America	Asia-Pacific	Global
<b>Revisit</b>	1 hour	1 hour	1 hour	1 day
<b>Status</b>	Detailed Design, Phase C	Instrument PDR July 2014	Instrument PDR complete	Instrument delivery 2015
<b>Launch</b>	2021 (Flight Acceptance Review first instrument)	No earlier than 11/2018	2018	Early 2016
<b>Payload</b>	UV-Vis-NIR 305-500, 750-775 nm	UV-Vis 290-490, 540-740 nm	UV-Vis 300-500 nm	UV-Vis-NIR-SWIR 270-500, 675-775, 2305-2385 nm
<b>Products</b>	O <sub>3</sub> , NO <sub>2</sub> , SO <sub>2</sub> , HCHO, AAI, AOD, height-resolved aerosol	O <sub>3</sub> , trop. O <sub>3</sub> , 0-2km O <sub>3</sub> , NO <sub>2</sub> , HCHO, SO <sub>2</sub> , CHOCHO, AOD, AAI	O <sub>3</sub> , NO <sub>2</sub> , SO <sub>2</sub> , HCHO, AOD	O <sub>3</sub> , NO <sub>2</sub> , SO <sub>2</sub> , HCHO, AAI, AOD, height-resolved aerosol, CO, CH <sub>4</sub>
<b>Spatial Sampling</b>	8 km x 8 km at 45N	2.1 km N/S x 4.7 km E/W @35N	3.5 km N/S x 8 km E/W @38N	7 km x 7 km nadir
<b>Nominal product resolution</b>	8.9 km N/S x 11.7 km E/W @40N	8.4 km N/S x 4.7 km E/W or better @35N (with 100W orbit)	7 km N/S x 8 km E/W @38N (gas), 3.5 km N/S x 8 km E/W @38N (aerosol)	7 km x 7 km nadir
<b>Notes</b>	Two instruments in sequence on MTG-S; use TIR sounder on MTG-S (expected sensitivity to O <sub>3</sub> and CO). Synergy with imager on MTG-I w.r.t. aerosol and clouds.	GEO-CAPE precursor or initial component of GEO-CAPE.  Synergy with GOES-R/S ABI w.r.t. aerosol and clouds.	Synergy with AMI and GOCI-2 instruments w.r.t. aerosol and clouds.	In formation with S-NPP for synergy w.r.t. clouds and O <sub>3</sub> .

# USA TEMPO mission

PI: Kelly Chance, Smithsonian Astrophysical Observatory

Deputy PI: Xiong Liu, Smithsonian Astrophysical Observatory

Instrument Development: Ball Aerospace

Instrument Project Manager: Wendy Pennington, NASA LaRC

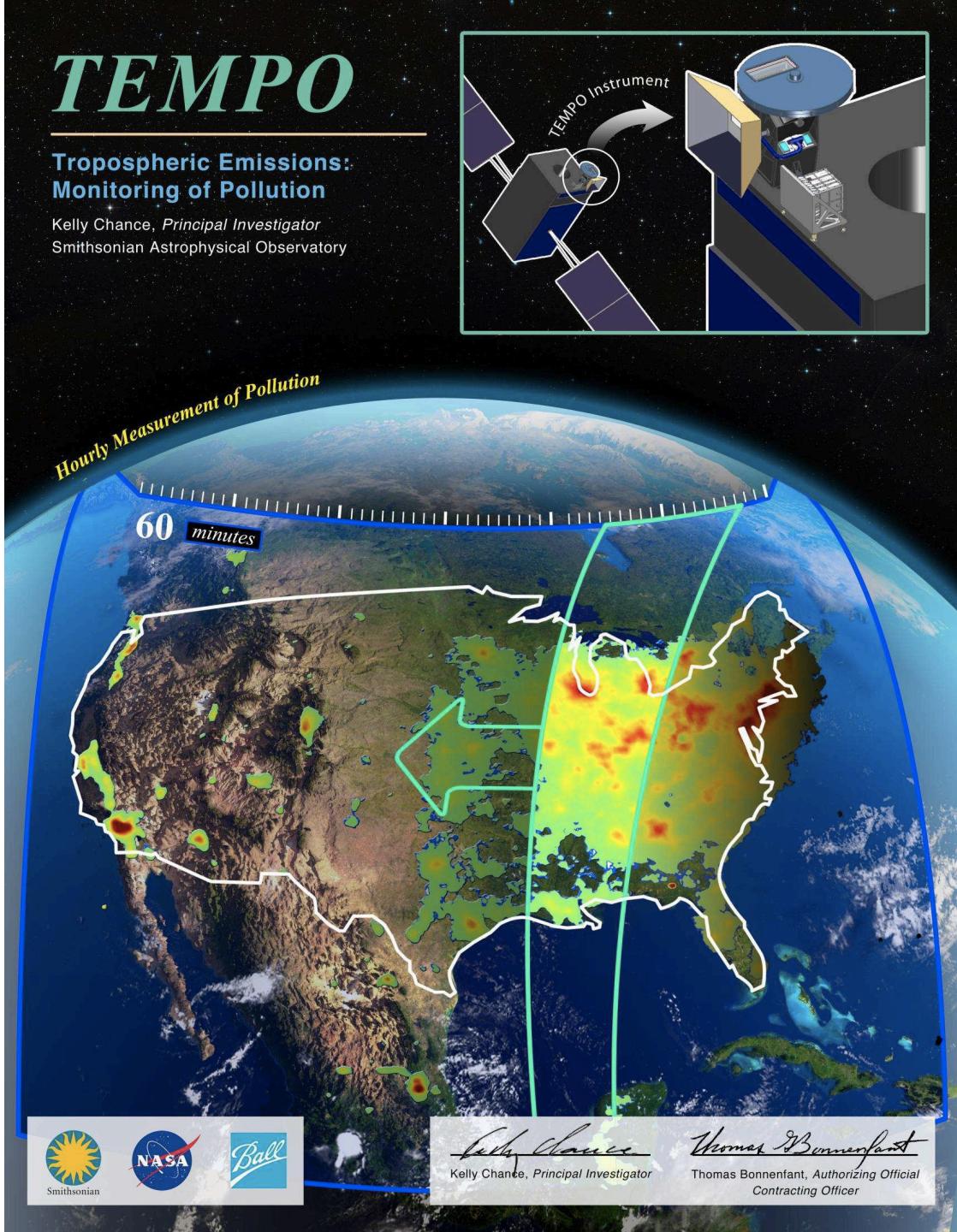
Mission Project Manager: Alan Little, NASA LaRC

Project Scientist: Dave Flittner, LaRC; Deputy PS: Jay Al-Saadi, LaRC

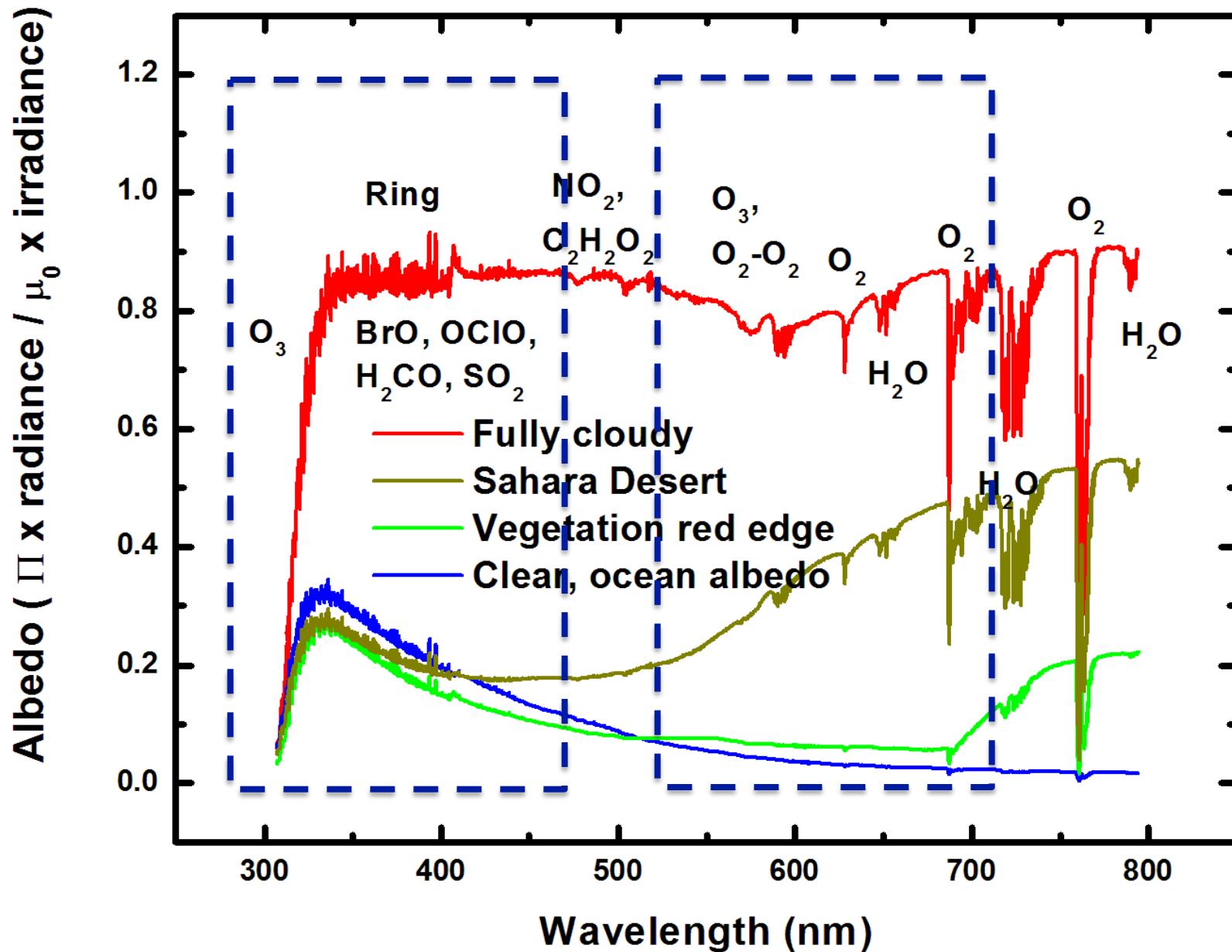
Other Institutions: NASA GSFC (led by Scott Janz), NOAA, EPA, NCAR, Harvard, UC Berkeley, St. Louis U, U Alabama Huntsville, U Nebraska

International collaboration: Korea, ESA/Eumetsat, Canada, Mexico

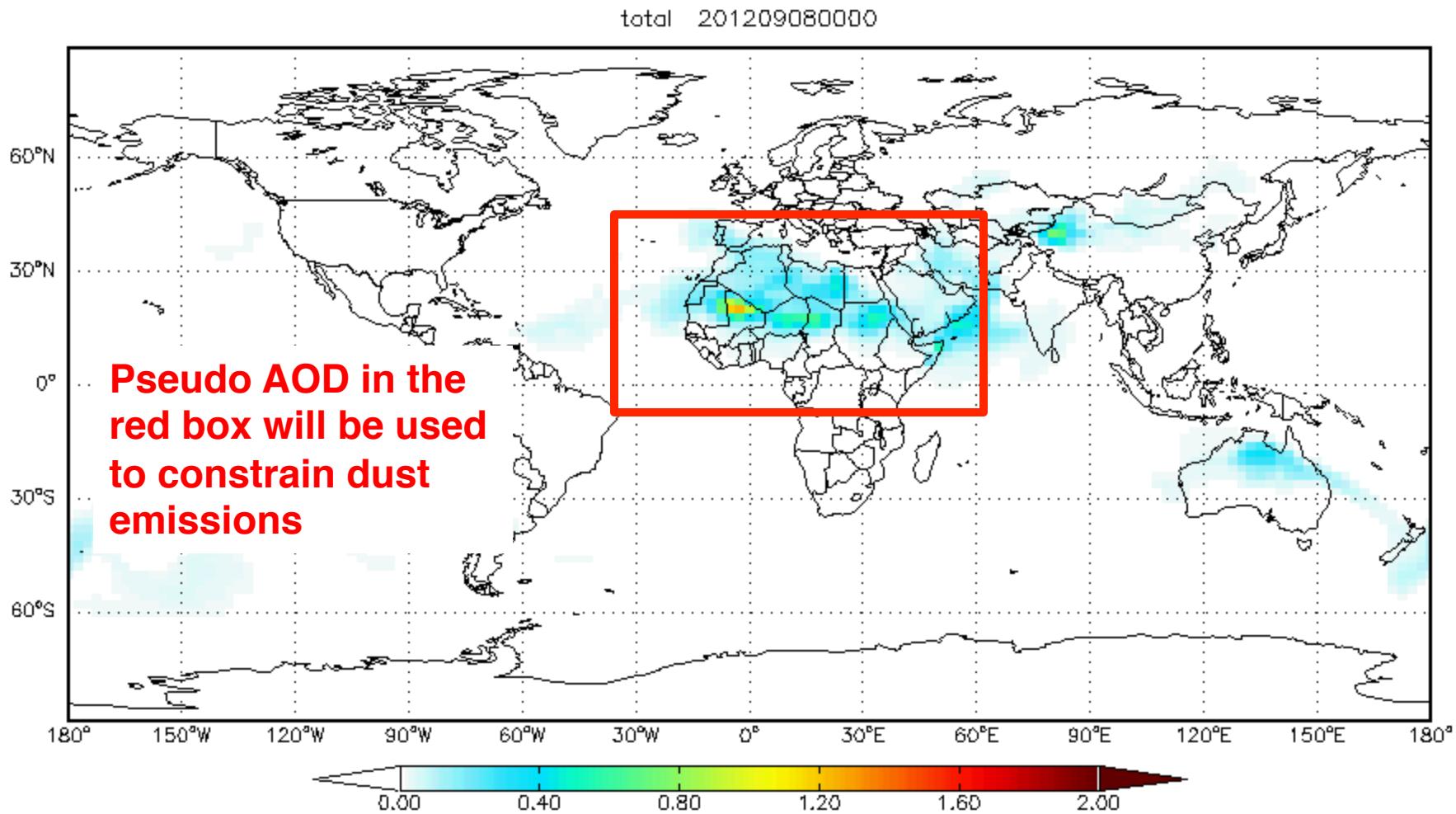
Selected Nov. 2012 through NASA's first Earth Venture Instrument solicitation



# TEMPO Spectral Range



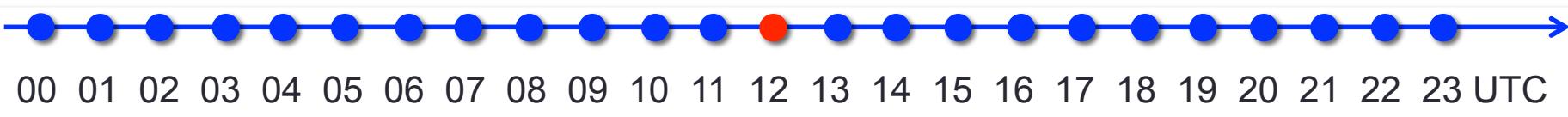
## Another example: using spectral information to constrain particle size in the dust emission



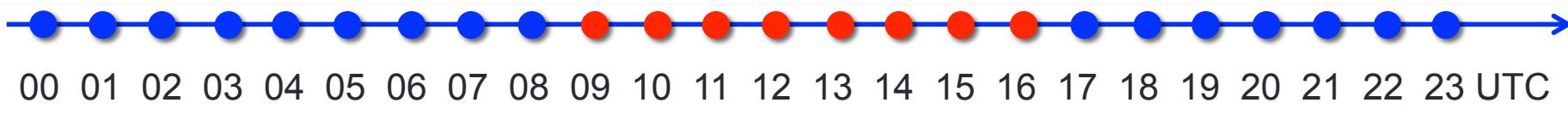
# OSSE Design

	DA 1	DA 2	DA 3	DA 4
Band	553 nm	1243 nm	2219 nm	553, 1243, and 2219 nm

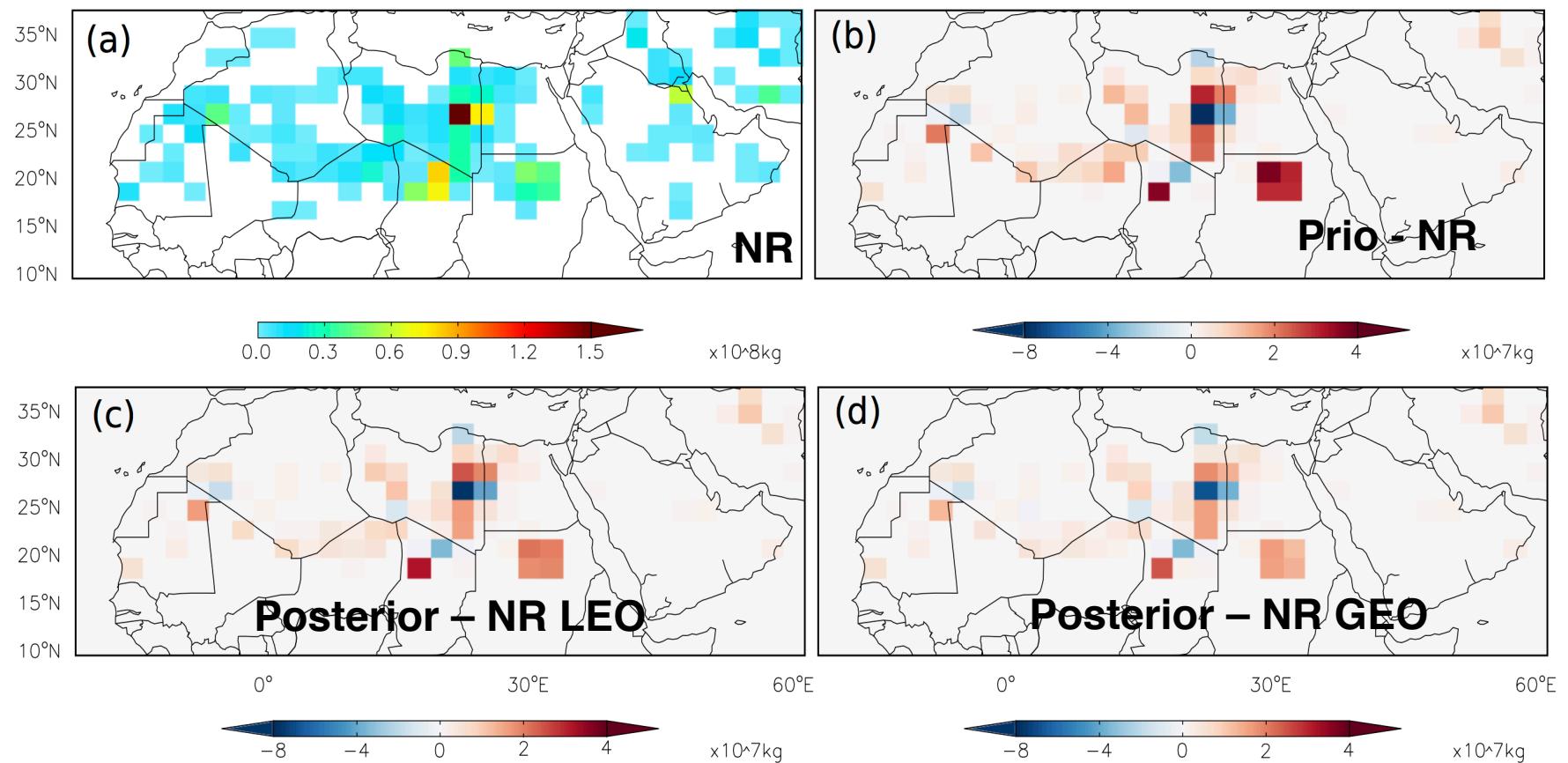
- Pseudo AOD observations have been removed when cloud fraction is larger than 0.2
- In every data assimilation (DA) experiment, two cases are conducted
  - Case A: Pseudo AOD is provided once a day (simulating polar satellite)



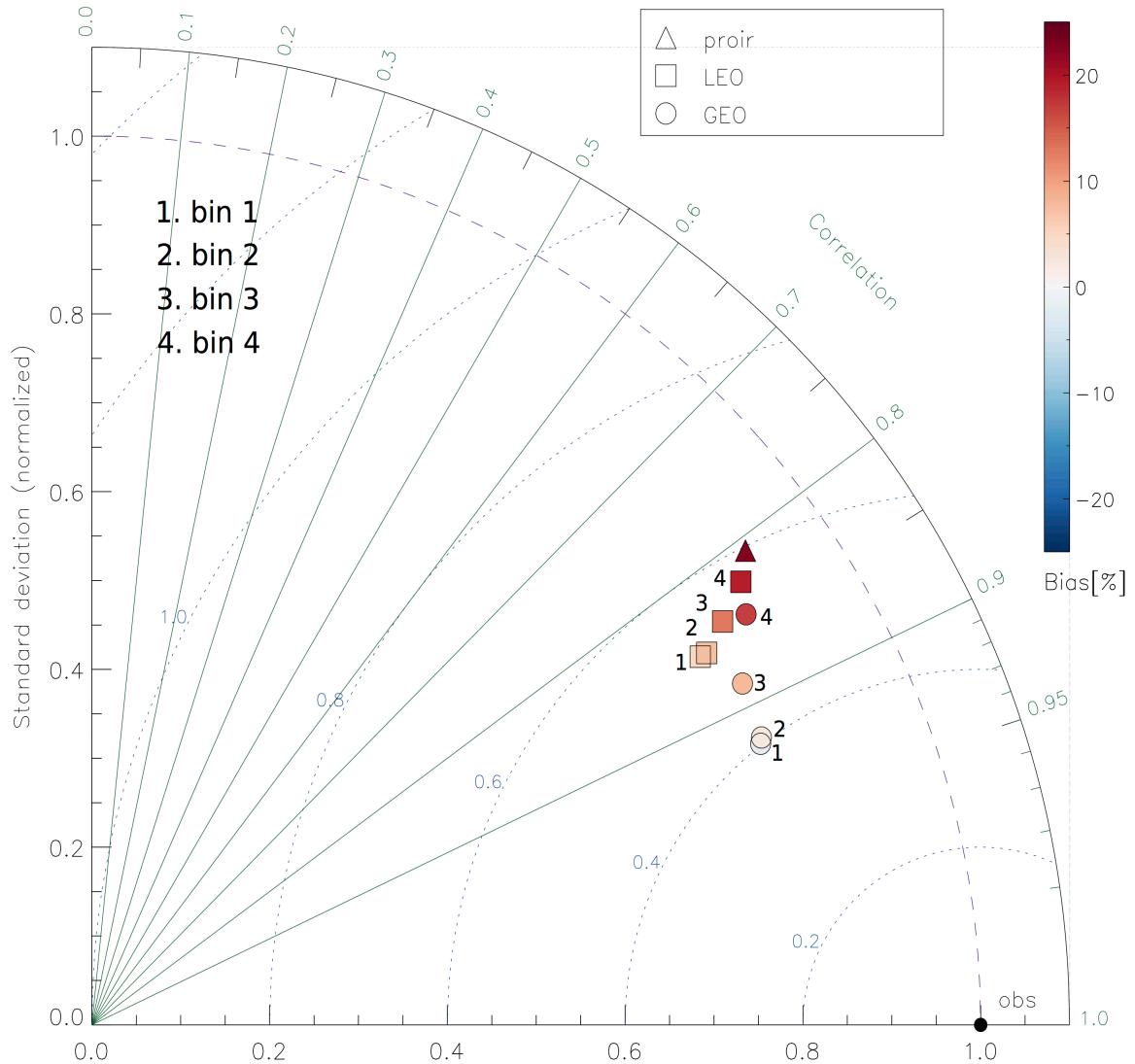
- Case B: Pseudo AOD is provided 8 times a day (simulating geostationary satellite)



# Results

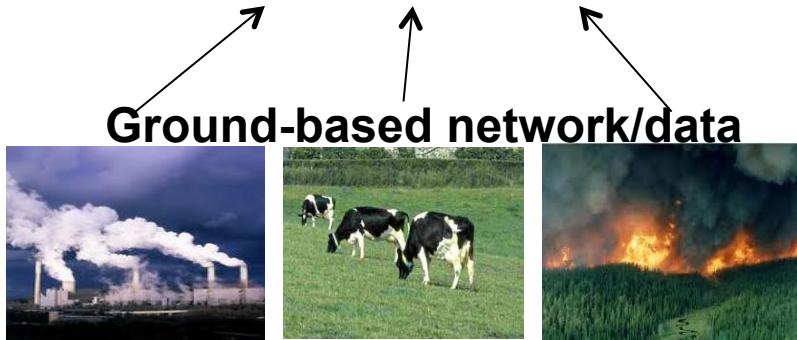


# Results



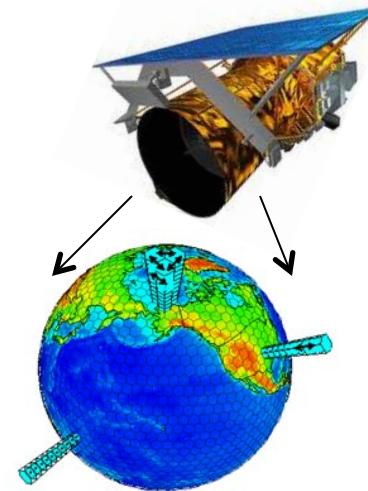
# Top-Down vs. Bottom-Up estimate of aerosol emission

## Bottom-up emission estimate



- Usually has a 2~3 yr lag
- Often seasonal or annual
- Point or area average
- Chemically speciated
- Lack of constraint on emission above the surface

## Top-down emission estimate

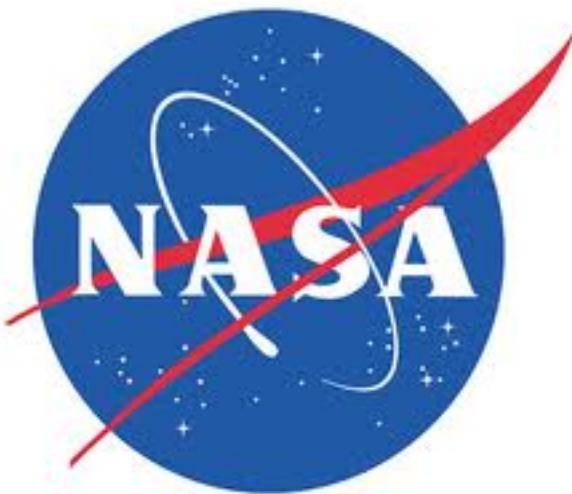


- Has the potential for near real time
- Daily (polar-orbiting) or higher (geo..)
- Globally with high spatial resolution
- Trace gases, & optical thickness
- Reflecting the columnar mass, and thus 1<sup>st</sup> order of emission

## Next steps

- One-step approach to use averaged reflectance to optimize dust emission and compare the results with two-step approach.
- Explore both short-wave and long-wave spectral information to constrain dust emission
  - Real data from GOME, SCIAMACHY, AIRS, and IASI.
  - Synthetic data from GEOS-Chem + UNL-VRTM
- Dust feedback will be analyzed by using FIM-Chem.
- Climate model output of dust concentration is needed.

**Thank you.**



# Forcing of each aerosol component

**Table 8.4 |** Global and annual mean RF ( $\text{W m}^{-2}$ ) due to aerosol–radiation interaction between 1750 and 2011 of seven aerosol components for AR5. Values and uncertainties from SAR, TAR, AR4 and AR5 are provided when available. Note that for SAR, TAR and AR4 the end year is somewhat different than for AR5 with 1993, 1998 and 2005, respectively.

	Global Mean Radiative Forcing ( $\text{W m}^{-2}$ )			
	SAR	TAR	AR4	AR5
<b>Sulphate aerosol</b>	−0.40 (−0.80 to −0.20)	−0.40 (−0.80 to −0.20)	−0.40 (−0.60 to −0.20)	−0.40 (−0.60 to −0.20)
<b>Black carbon aerosol from fossil fuel and biofuel</b>	+0.10 (+0.03 to +0.30)	+0.20 (+0.10 to +0.40)	+0.20 (+0.05 to +0.35)	+0.40 (+0.05 to +0.80)
<b>Primary organic aerosol from fossil fuel and biofuel</b>	Not estimated	−0.10 (−0.30 to −0.03)	−0.05 (0.00 to −0.10)	−0.09 (−0.16 to −0.03)
<b>Biomass burning</b>	−0.20 (−0.60 to −0.07)	−0.20 (−0.60 to −0.07)	+0.03 (−0.09 to +0.15)	−0.0 (−0.20 to +0.20)
<b>Secondary organic aerosol</b>	Not estimated	Not estimated	Not estimated	−0.03 (−0.27 to +0.20)
<b>Nitrate</b>	Not estimated	Not estimated	−0.10 (−0.20 to 0.00)	−0.11 (−0.30 to −0.03)
<b>Dust</b>	Not estimated	−0.60 to +0.40	−0.10 (−0.30 to +0.10)	−0.10 (−0.30 to +0.10)
<b>Total</b>	Not estimated	Not estimated	−0.50 (−0.90 to −0.10)	−0.35 (−0.85 to +0.15)

## Retrieve-then-average vs. Average-then-retrieve?

The Jacobians of monthly-averaged normalized radiance (e.g., reflectance) with respect to AOD can be obtained from hourly outputs:

$$\frac{\partial(R_1 + R_2 + \dots)/N}{\partial\tau_{avg}} = \frac{1}{N} \left[ \frac{\partial R_1}{\partial\tau_1} \frac{\partial\tau_1}{\partial\tau_{avg}} + \frac{\partial R_2}{\partial\tau_2} \frac{\partial\tau_2}{\partial\tau_{avg}} + \dots \right]$$

because  $\tau_{avg} = (\tau_1 + \tau_2 + \dots)/N$ , we have  $\partial\tau_1/\partial\tau_{avg} = N$ . With similar derivations, we obtain:

### Spectral fingerprint linearity

$$\frac{\partial(R_1 + R_2 + \dots)/N}{\partial\tau_{avg}} = \frac{\partial R_1}{\partial\tau_1} + \frac{\partial R_2}{\partial\tau_2} + \dots \quad \swarrow$$

Since each term on the right-hand side of the above equation is readily computed with our simulator (UNL-VRTM + GEOS-Chem), the left-hand of this equation can be readily obtained. Similarly, we can show that

$$\frac{\partial(R_1 + R_2 + \dots)/N}{\partial\omega_{avg}} = \frac{\partial R_1}{\partial\omega_1} \frac{\tau_{avg}}{\tau_1} + \frac{\partial R_2}{\partial\omega_2} \frac{\tau_{avg}}{\tau_2} + \dots$$

Thus, through the chain rule, we can derive Jacobians of reflectance to other aerosol properties (such as particle size and height) by using what we computed on the daily basis, which will then be used to derive DFS. This DFS (e.g., from the mean of reflectance) will then be compared with averages of instantaneous DFS.

**This will answer if average-then-retrieve gives mean state of emission.**